Large-Format Arrays of Thermal Detectors

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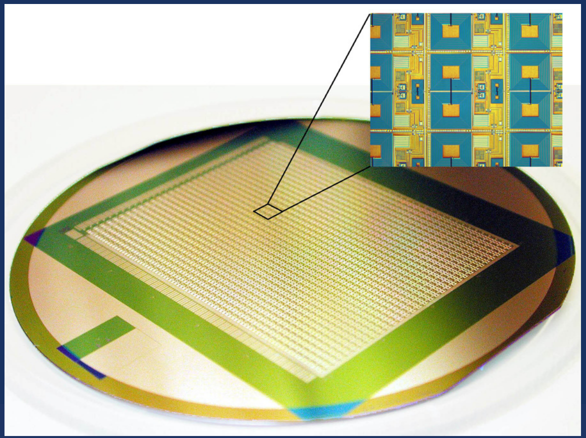
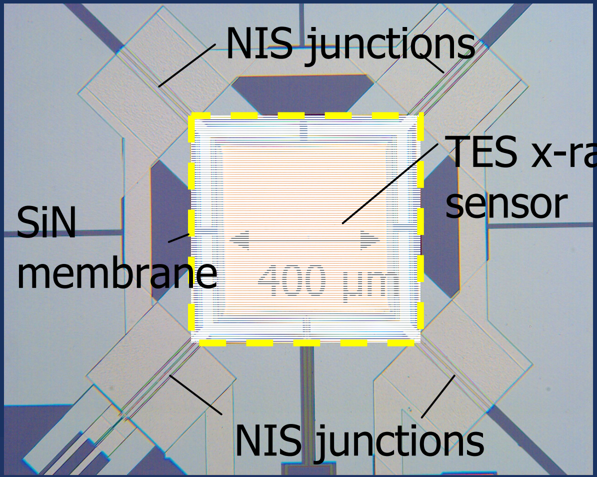
From Spitzer to Herschel and Beyond

What do we need to go beyond Herschel?

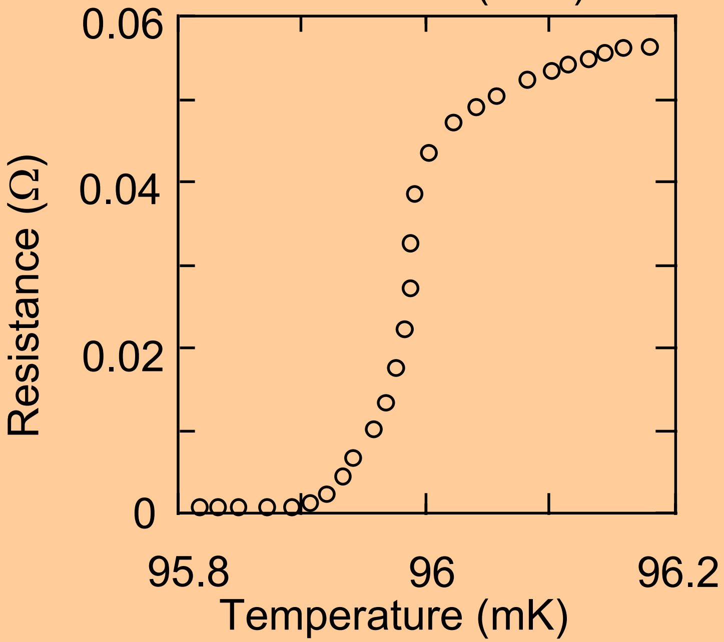
- Larger detector arrays
  - Fabrication & multiplexed readout
- More sensitive pixels
  - Pixel engineering & on-chip refrigeration
- Polarization-sensitive pixels

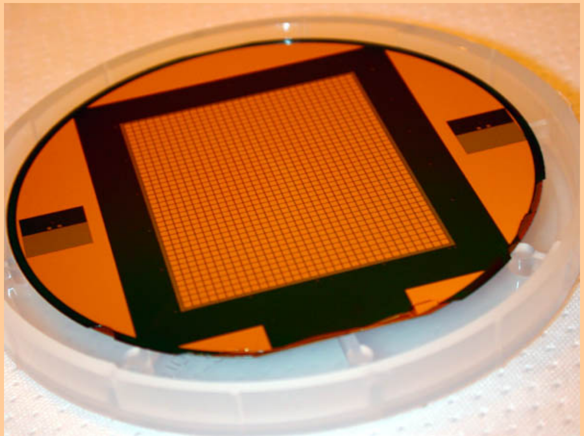




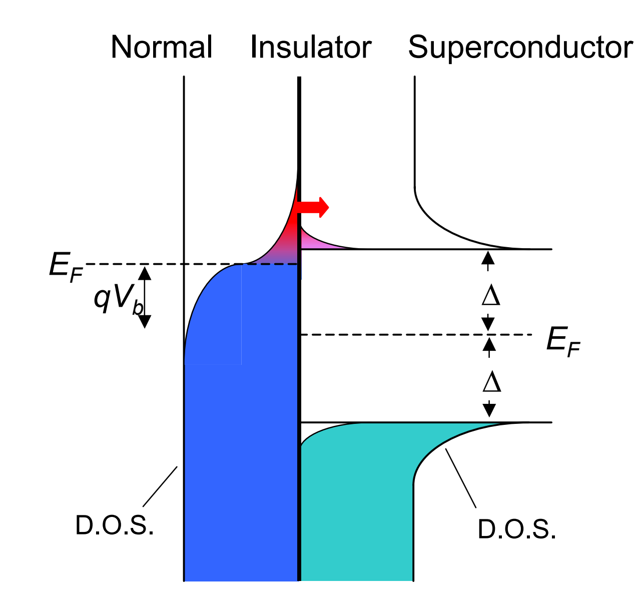
Bolometers

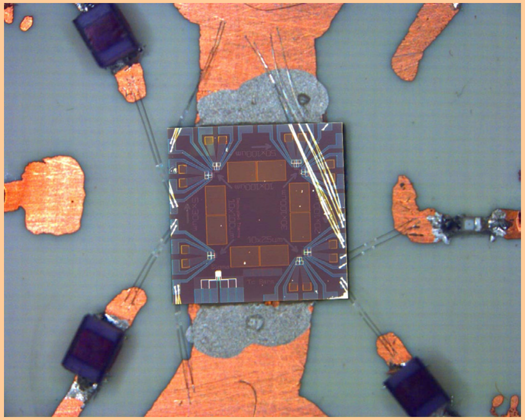
Transition-Edge Thermometer (TES)





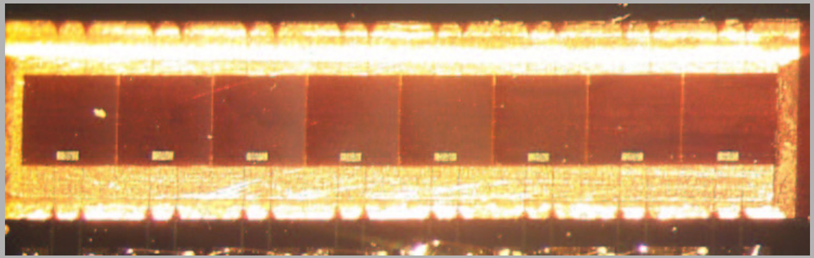
Normal-Insulator-Superconductor (NIS) tunnel junction thermometer



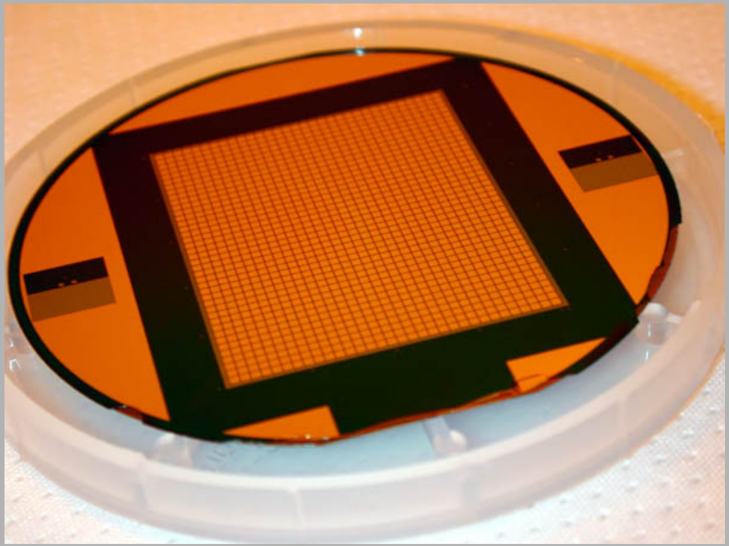


Large TES arrays

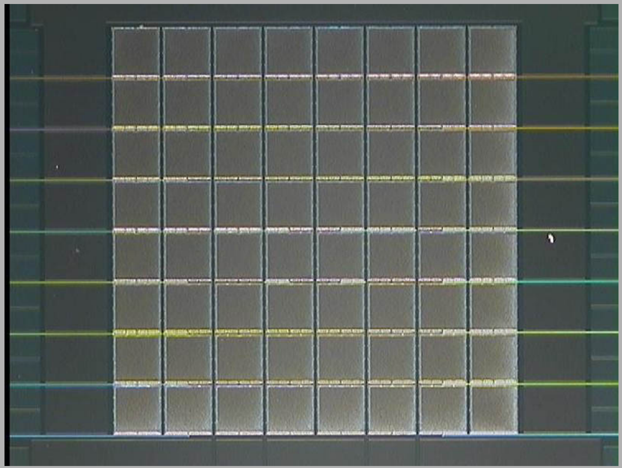
8-pixel FIBRE array (with GSFC)

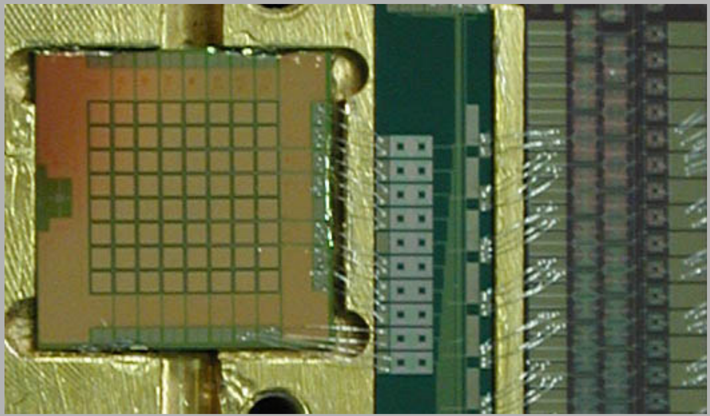


1,280-pixel SCUBA-2 subarray (with the UKATC and the U of E)

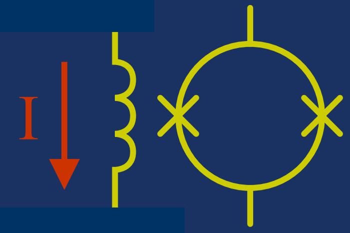


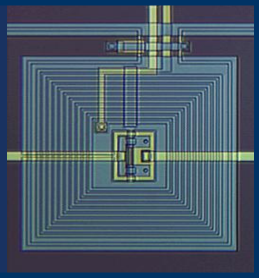
64-pixel x-ray microcalorimeter array



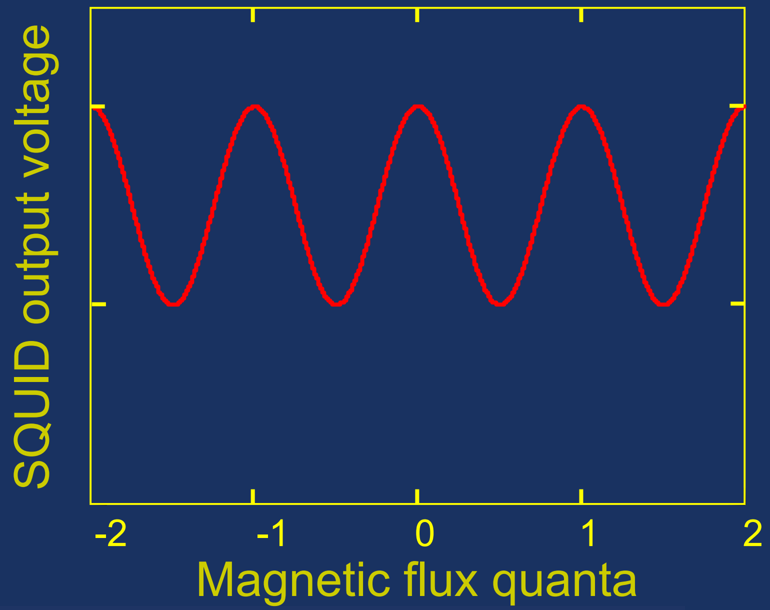


SQUID Current Amplifier





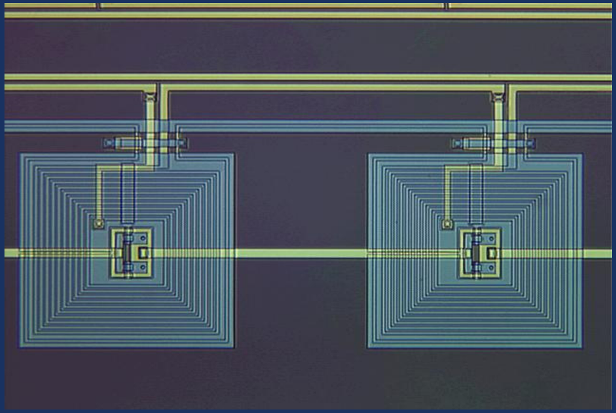
- Superconducting Quantum Interference Devices (SQUIDs)
- The most sensitive devices for the measurement of magnetic fields.
- Quantum interference between two Josephson tunnel junctions, analagous to a two-slit interferometer.
- Output voltage is a periodic function of the applied magnetic flux.



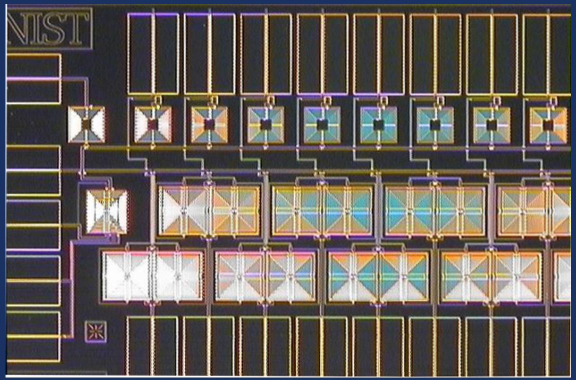
SQUID Fabrication

- Nb/Al/Al_2O_3/Nb trilayer technology
- Low temperature (30 C) ECR PECVD SiO_2
- Two wiring and dielectric levels
- PdAu shunt and damping resistors
- 12 lithography levels

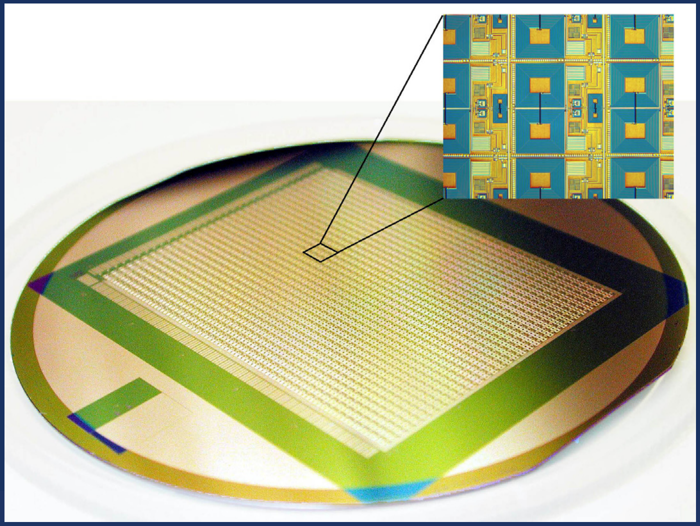
100-SQUID Series Array for the Cryogenic Dark Matter Search, APEX-SZ, and the SPT



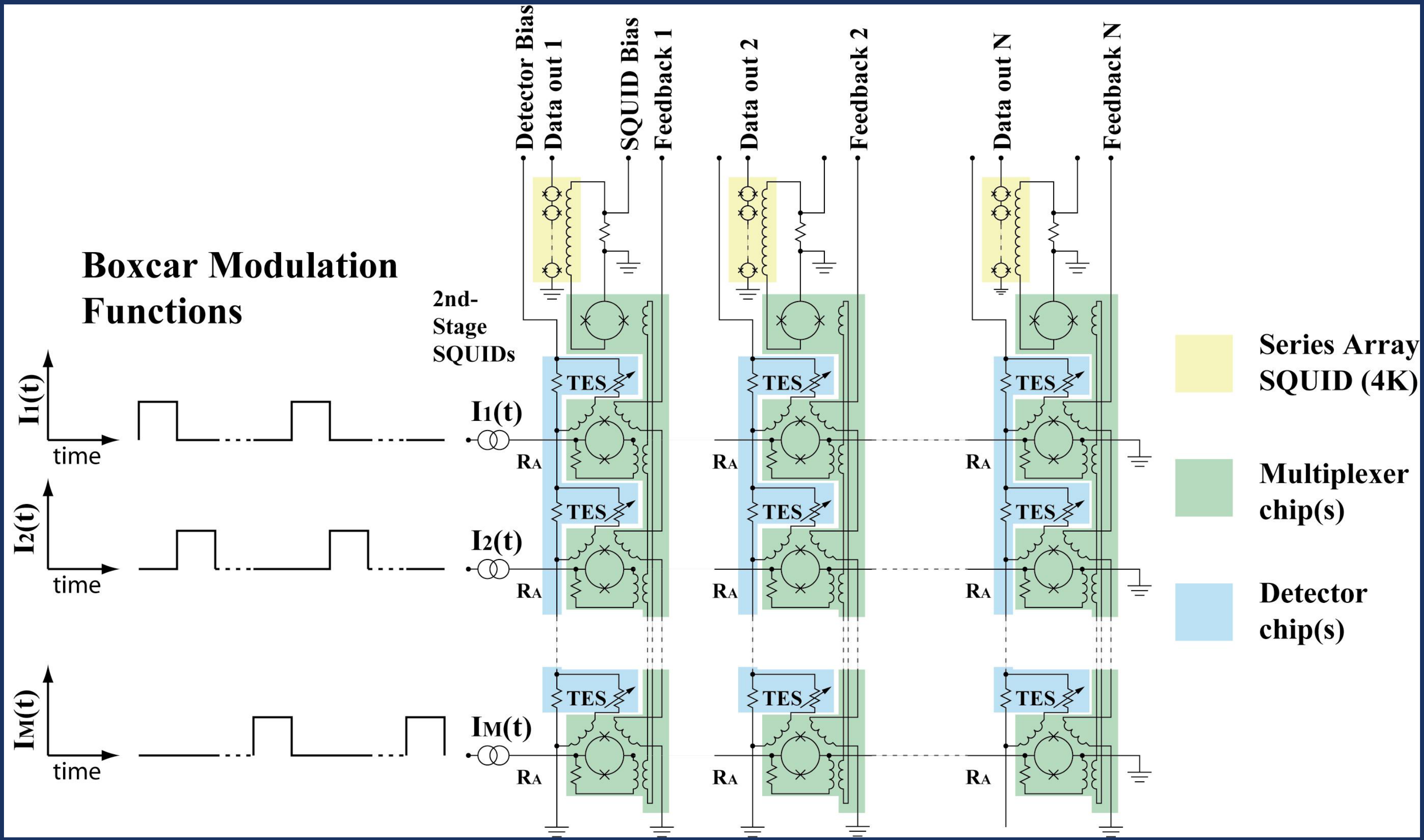
1 × 32 MUX Array for ACT/Penn Array/SAFIRE-SOFIA etc.



32 × 40 MUX Array for SCUBA-2

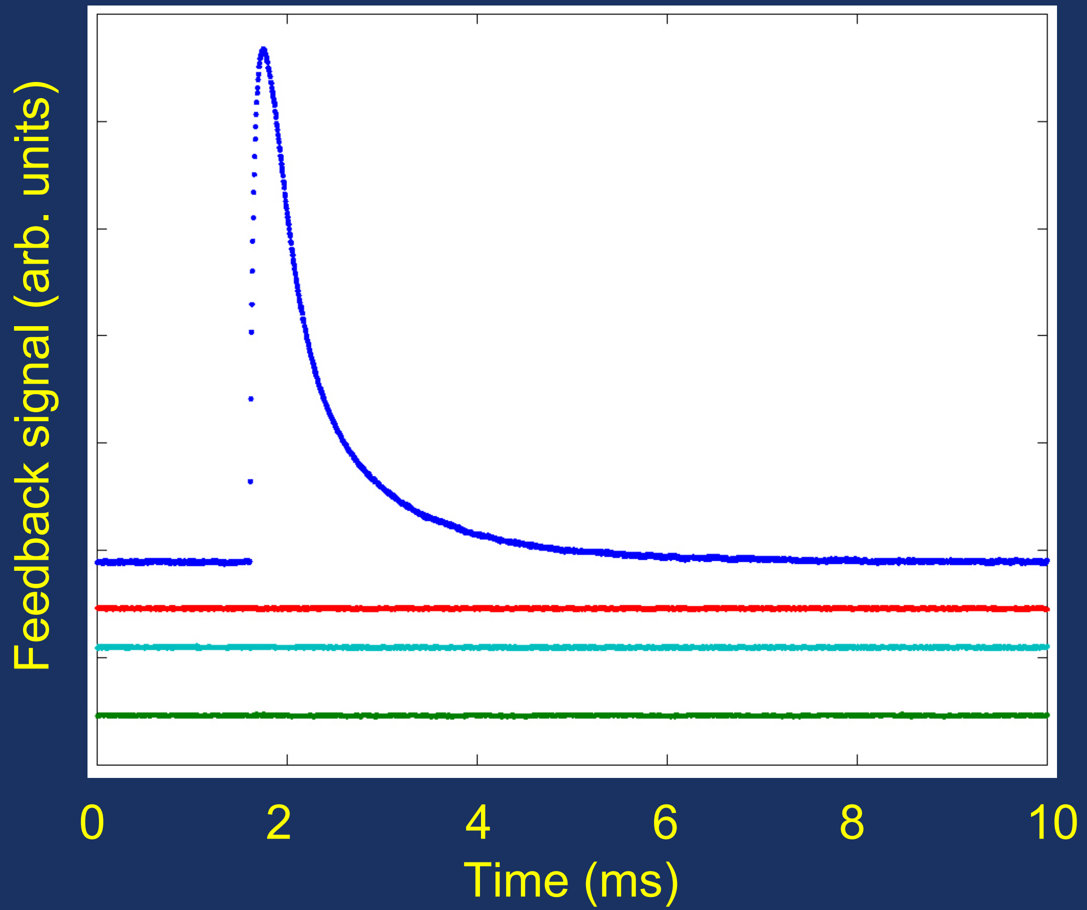


Time-Division Multiplexer

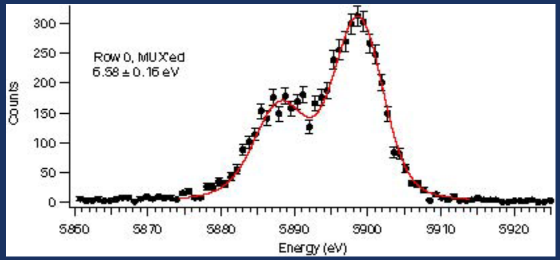


- One SQUID for each pixel
- SQUIDs are switched on one at a time
- If Nyquist criterion is met with low-noise SQUIDs, signal is reconstructed without loss.

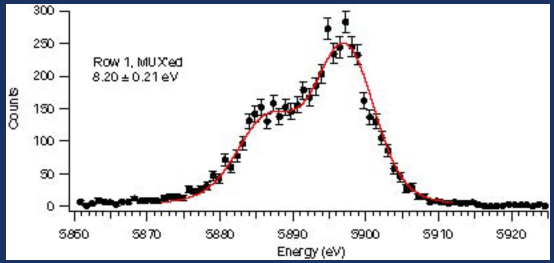
MUXed x-rays



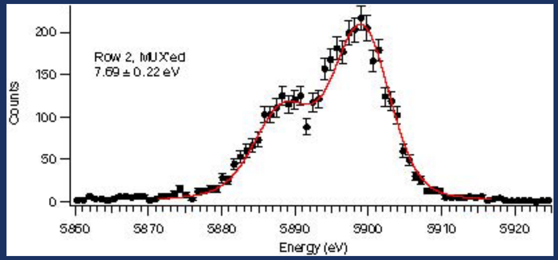
Feedback signal (arb. units)
0
2
4
6
8
10
Time (ms)



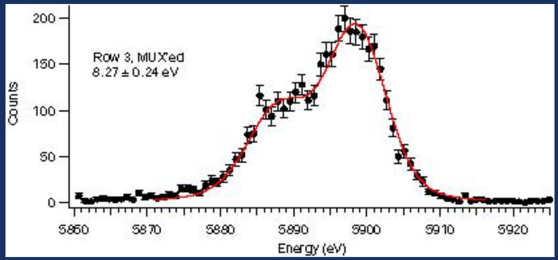
Row 0, MUXed
6.58 ± 0.16 eV
Counts
0
50
100
150
200
250
300
5850
5870
5880
5890
5900
5910
5920
Energy (eV)



Row 1, MUXed
8.20 ± 0.21 eV
Counts
0
50
100
150
200
250
300
5850
5870
5880
5890
5900
5910
5920
Energy (eV)

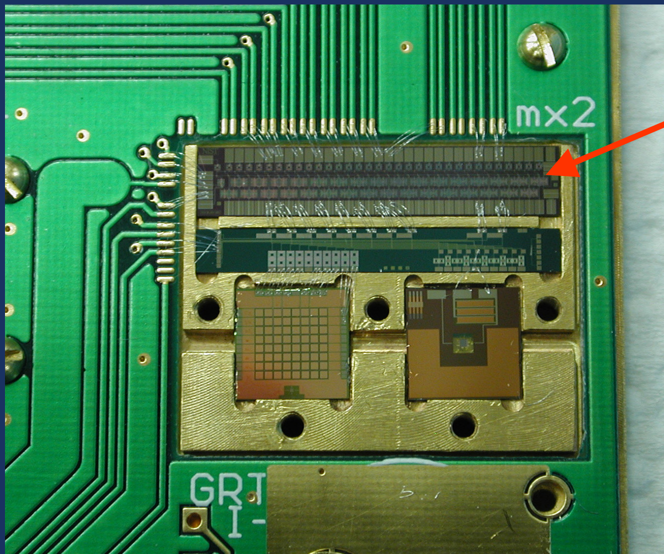


Row 2, MUXed
7.69 ± 0.22 eV
Counts
0
50
100
150
200
5850
5870
5880
5890
5900
5910
5920
Energy (eV)

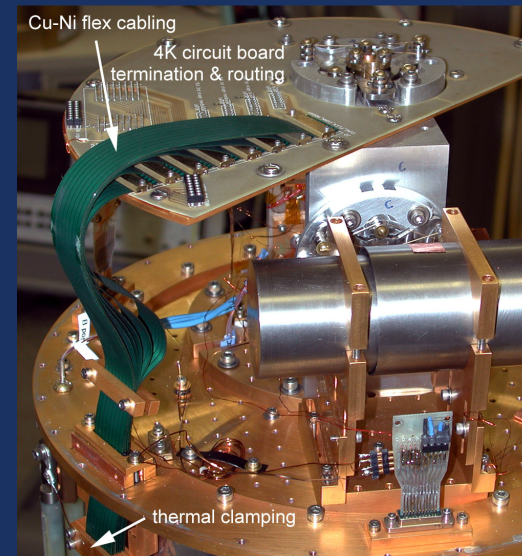


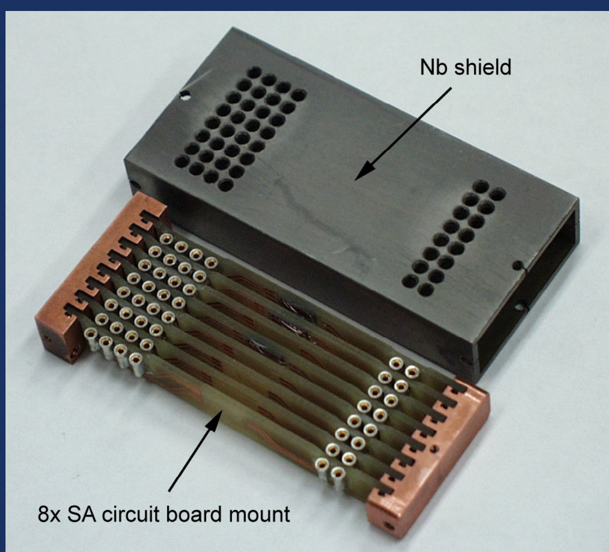
Row 3, MUXed
8.27 ± 0.24 eV
Counts
0
50
100
150
200
5850
5870
5880
5890
5900
5910
5920
Energy (eV)

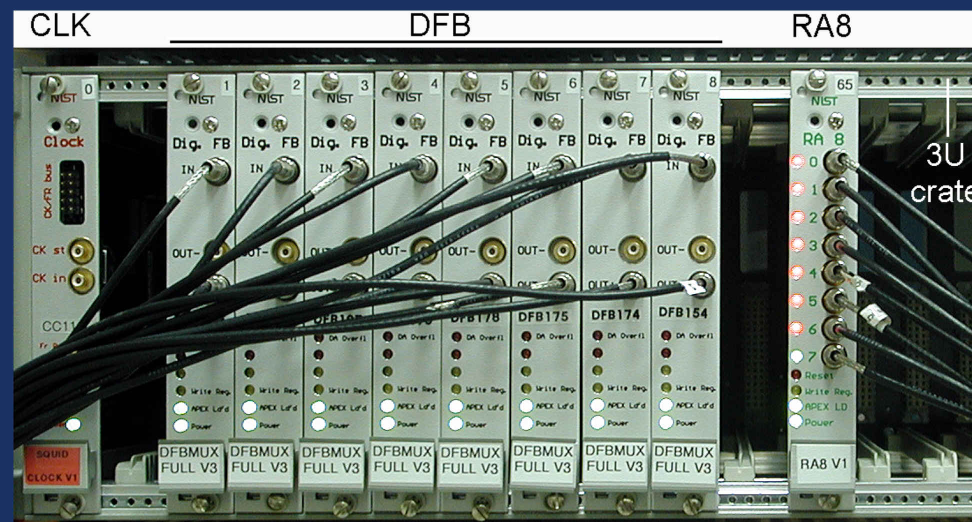
Readout electronics



MUX chip

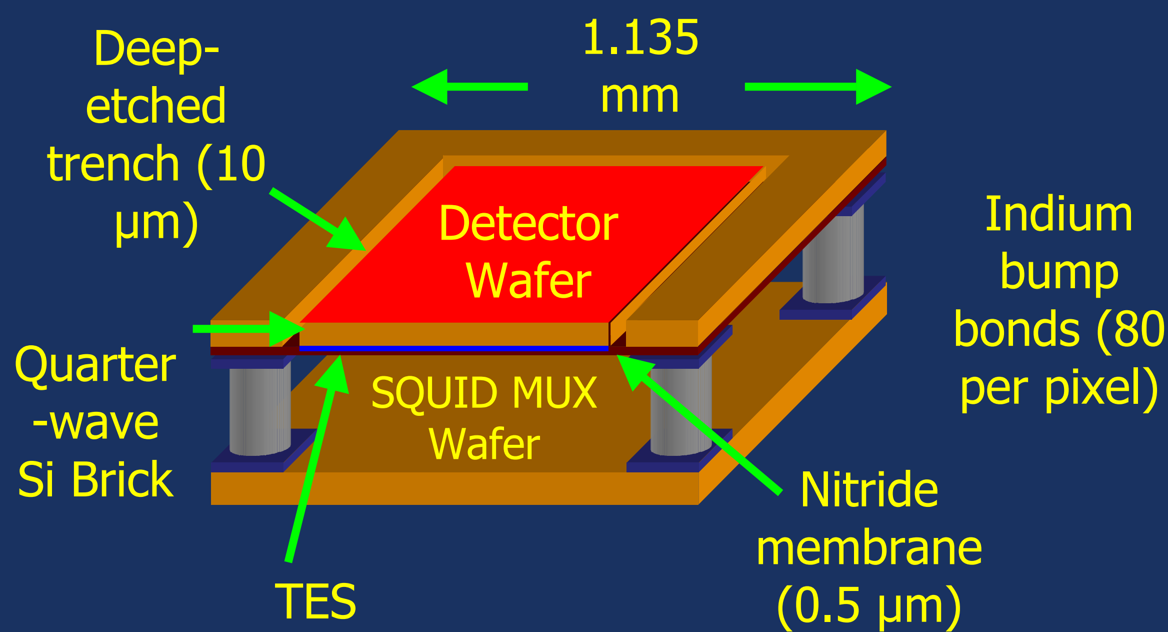




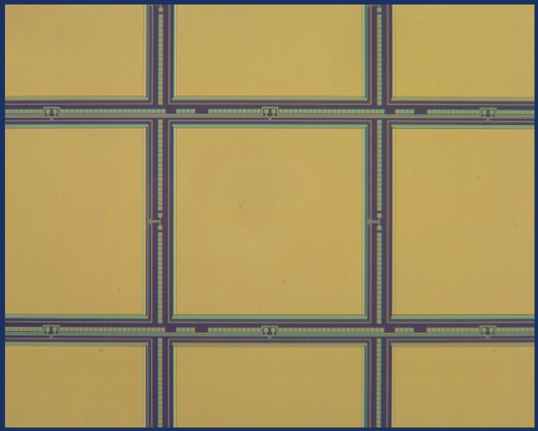


3U crate with room-temperature electronics for 8×32 array

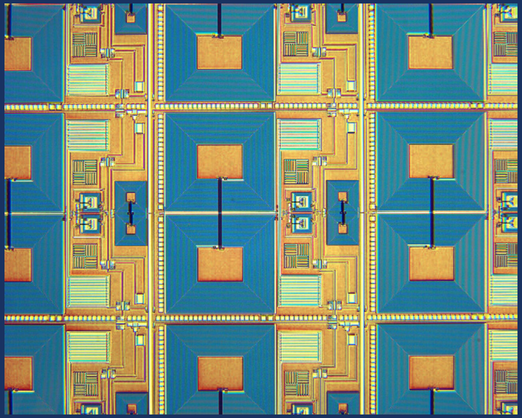
SCUBA-2 Bolometer Pixel Architecture



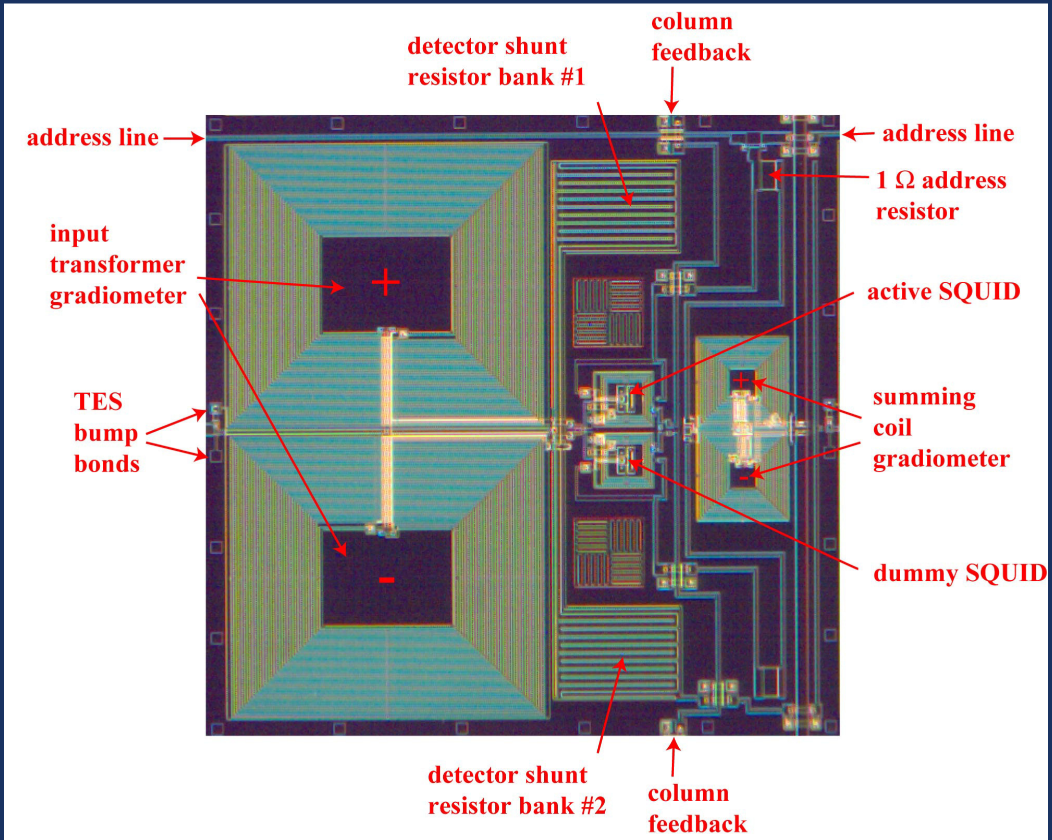
TES bolometer pixels



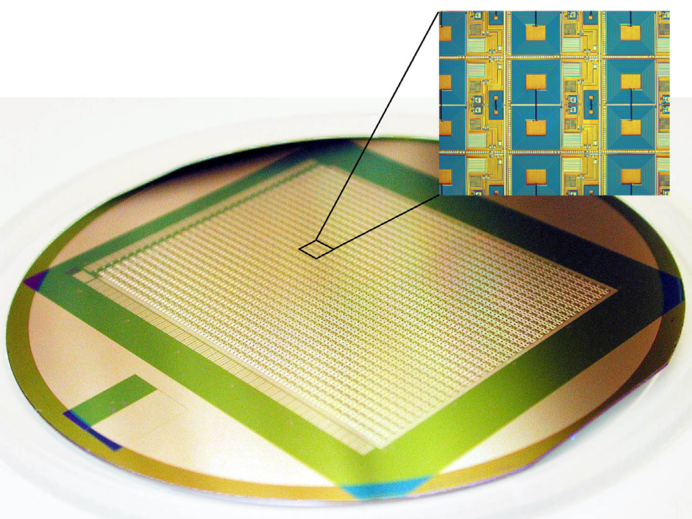
SQUID MUX pixels



In-focal-plane multiplexer (SCUBA-2)

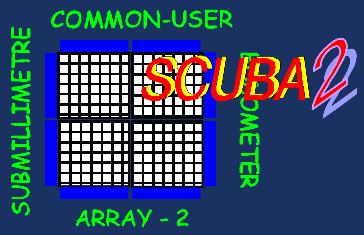


Single pixel from array



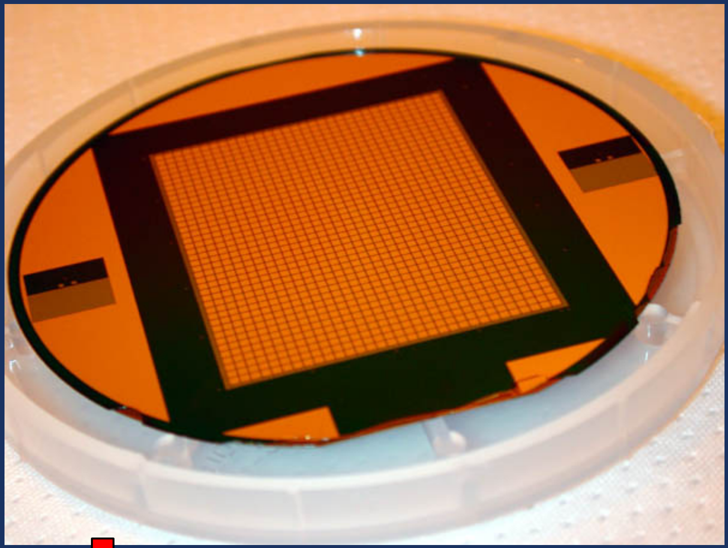
1,280-pixel array chip

SCUBA-2 850 μm Subarray Complete

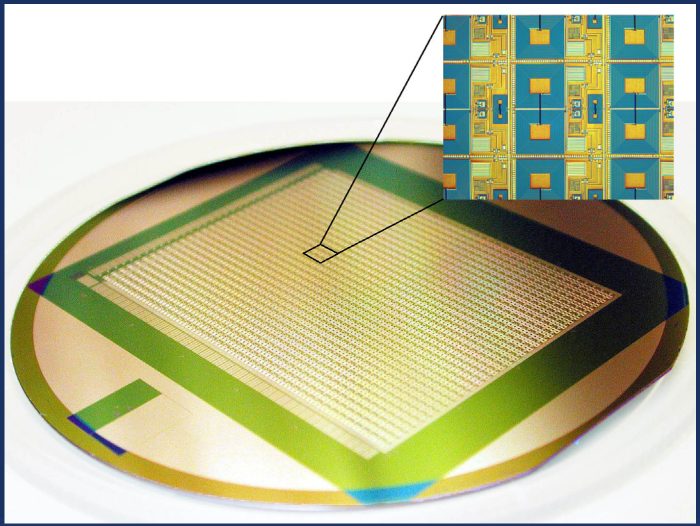


- SCUBA-2 will consist of 10,240 TES bolometer pixels (half at 450 μm, half at 850 μm) on the JCMT in 2006.
- The first 1,280-pixel 850 μm subarray is completed

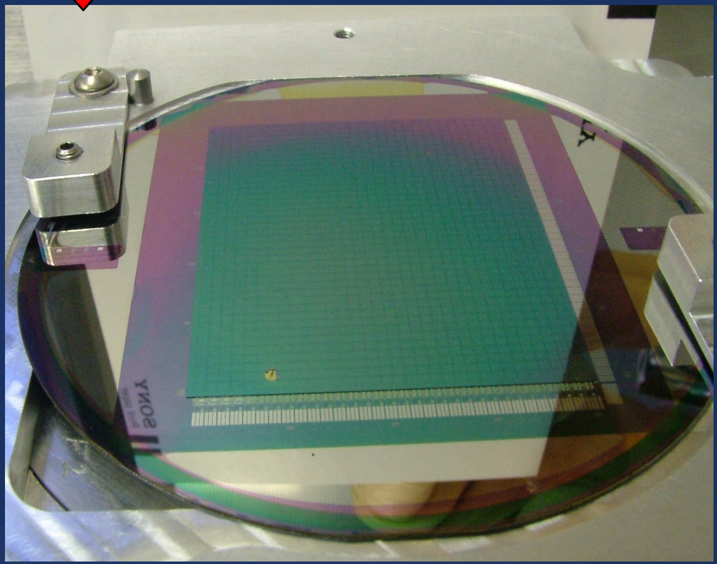
1,280-pixel TES bolometer



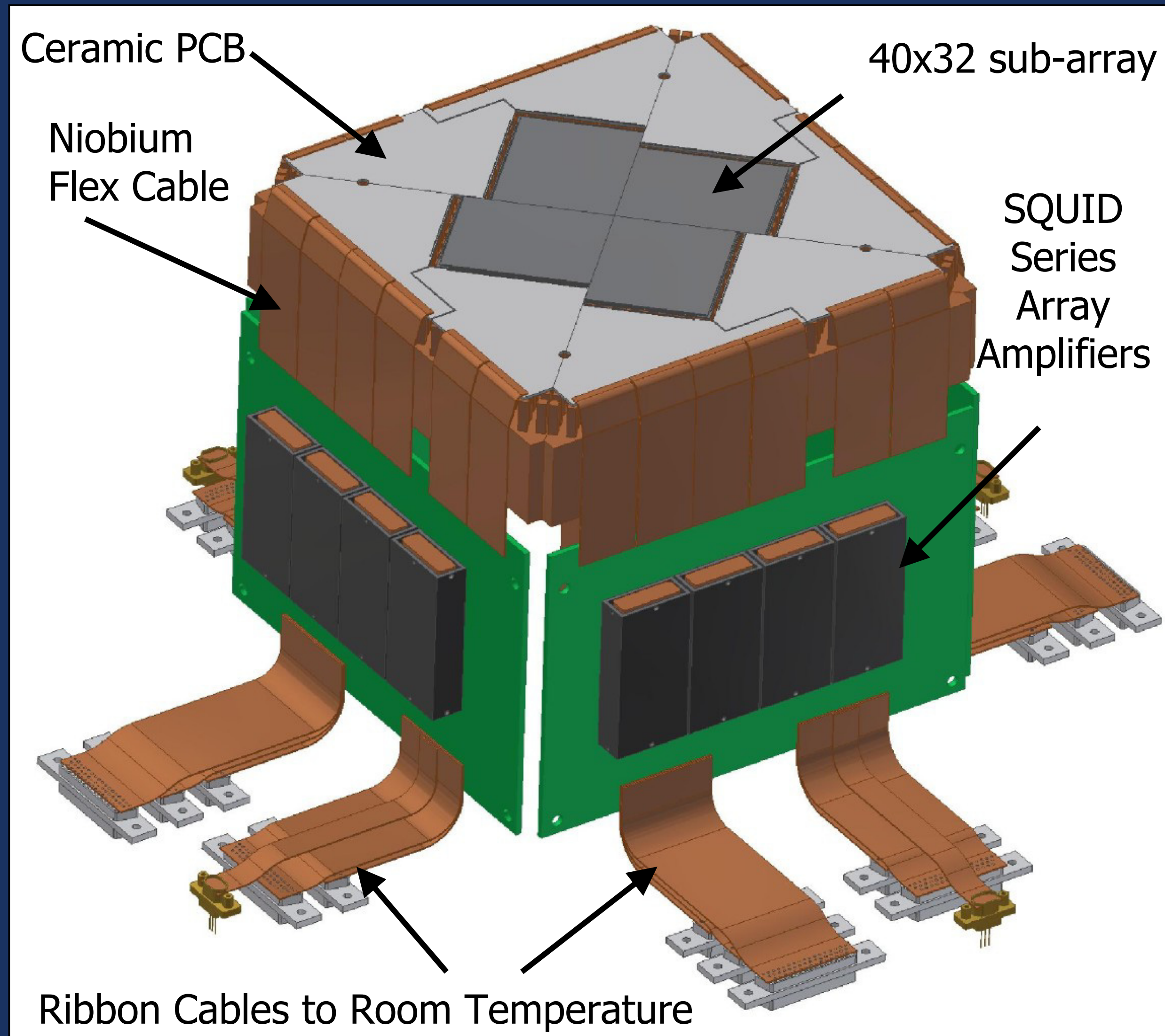
1,280-pixel SQUID Multiplexer



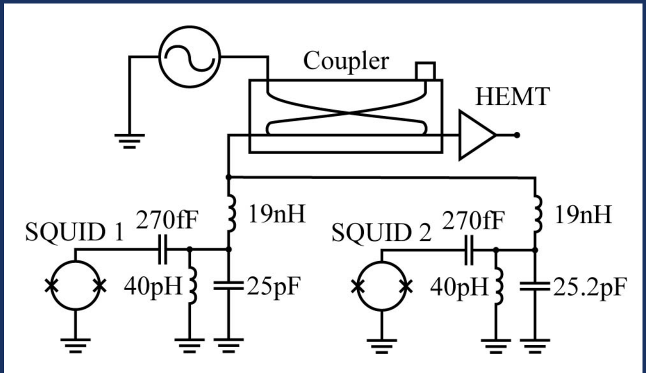
bump-bonded subarray (TES+MUX)



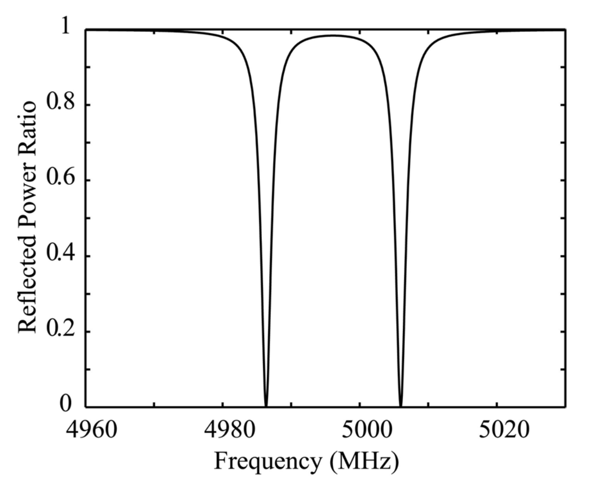
SCUBA-2 array module



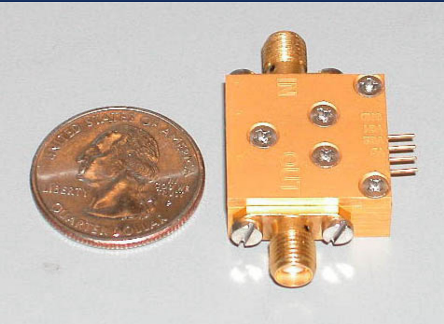
Towards larger cameras: microwave MUX



Straw-man circuit: Q ~ 4000
(distributed resonators also possible)



Calculated reflected power at impedance match



2-12 GHz HEMT with < 5 K noise temperature

- Present MUX techniques are sufficient for ~10 kpixels
- Much larger arrays at shorter wavelengths require larger bandwidth in the MUXed channel
- Multiplexing of two-pixels demonstrated with excellent noise performance ($0.5\ \mu\Phi_0/\mathrm{Hz}^{1/2}$)
- Multiplex thousands of SQUIDs in one HEMT amplifier channel
- Room-temperature electronics are challenging

More sensitive bolometers

We need to improve pixel sensitivity by ~2 orders of magnitude, requiring lower bolometer thermal conductance or operational temperature.

- Smaller, carefully engineered leads on isolated pixels
- or, small volume with planar antenna coupling

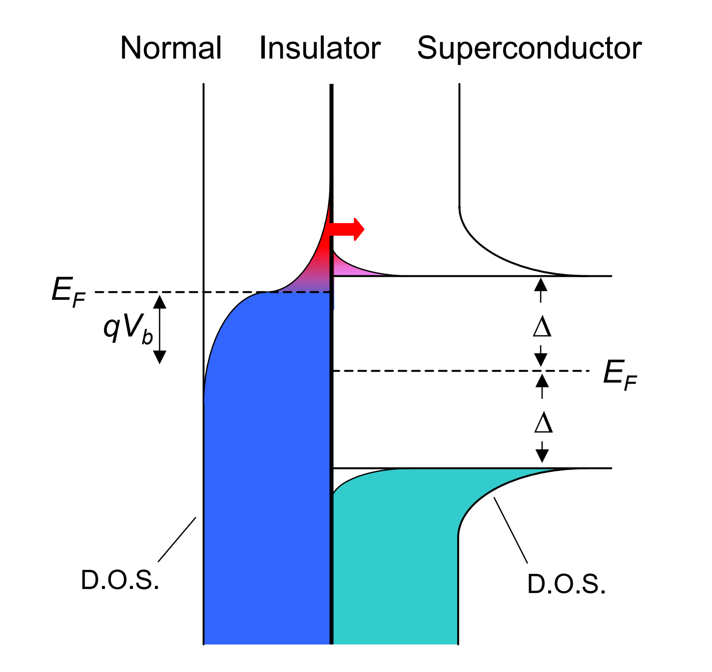
  $NEP_{\text{electron-phonon}} \propto Vol^{1/2}$
- or, much lower temperatures (~10 mK?)

  $NEP_{\text{electron-phonon}} \propto T^{3}$

Reading out more sensitive pixels is *not* much harder, although you need filters to protect the pixel from the amplifier power.

On-Chip Microrefrigerators for FIR-mm detectors

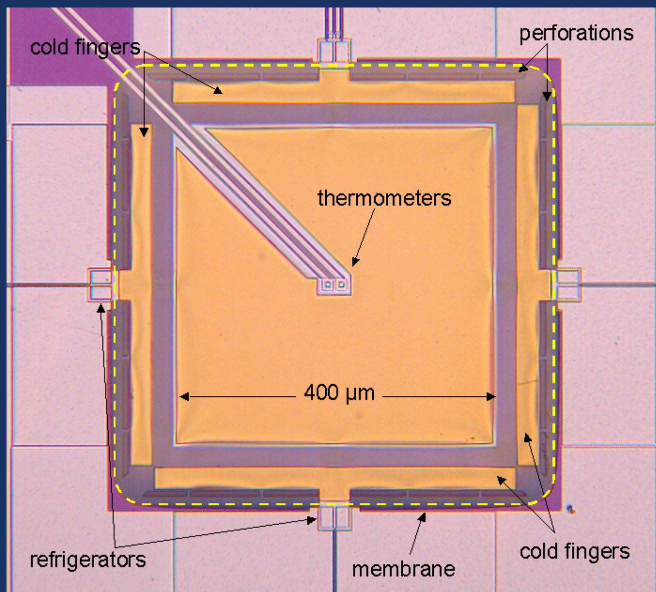
- On-chip microrefrigerators can be integrated with cryogenic sensors, easing the requirements on ADRs, and allowing lower temperatures.
- Demonstrated cooling from 260 mK to 110 mK, and "surplus" cooling power of 50 pW (enough for detectors)
- Cooling from 260 mK $\rightarrow$ 70 mK possible
- Cooling from 50 mK $\rightarrow$ < 10 mK possible
- Cooling from 600 mK possible in multistage device

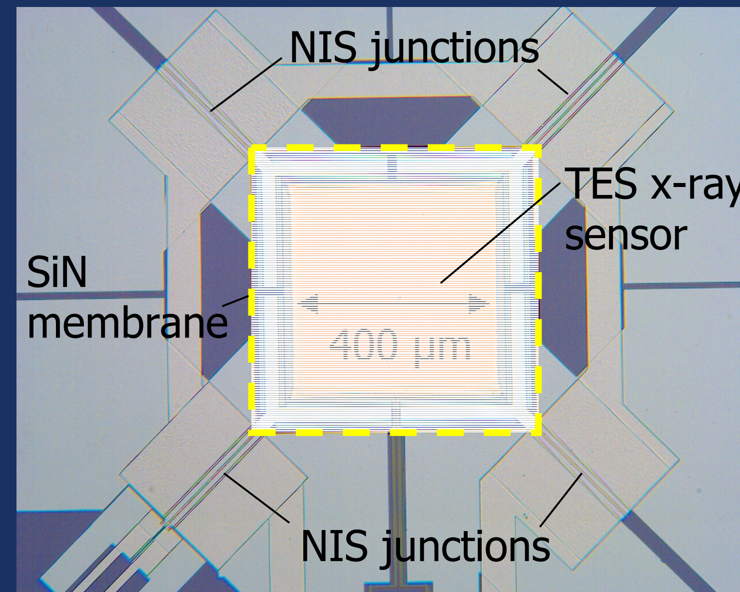


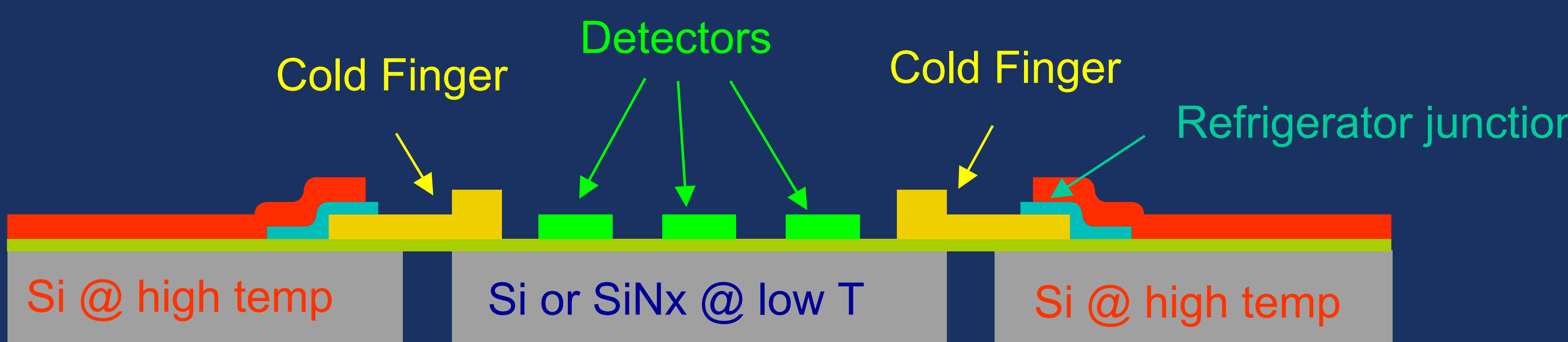
$\rightarrow$ hottest electrons moved from normal metal into superconductor (superconducting Peltier cooler)

On-chip cooled platform

NEP $_{\text{electron-phonon}} \propto$ Vol $^{1/2}$ T^3 $\rightarrow$ Ultra-low NEP much easier at low T

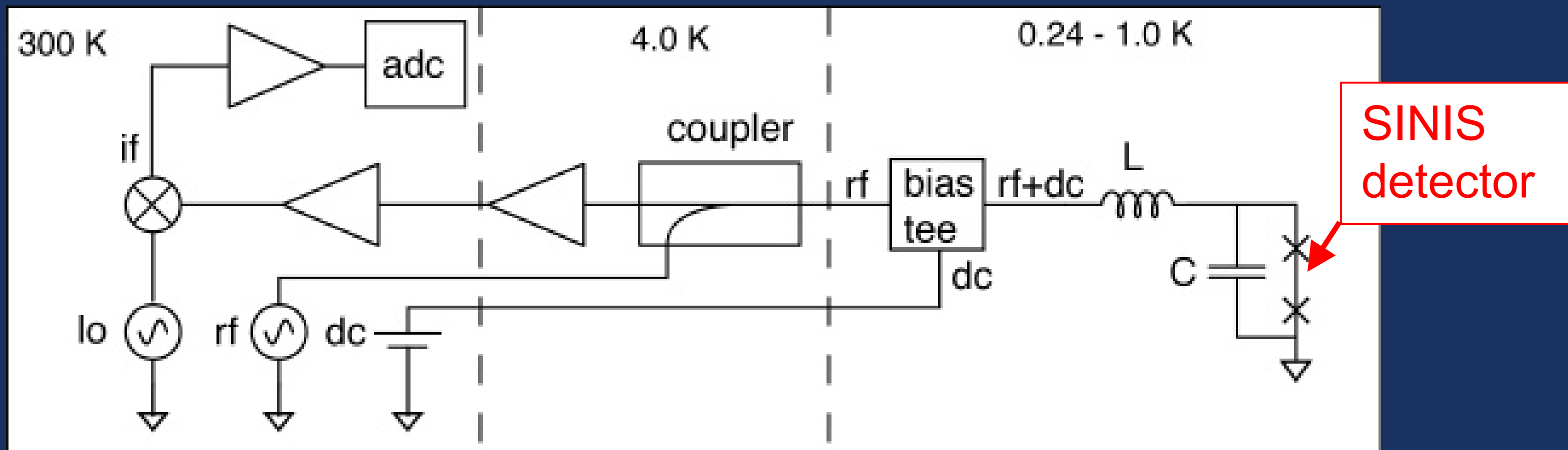




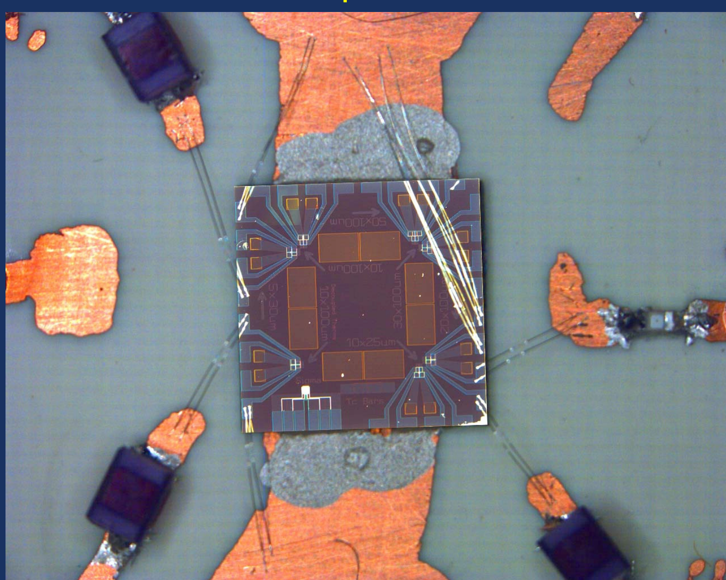


Microwave NIS detectors

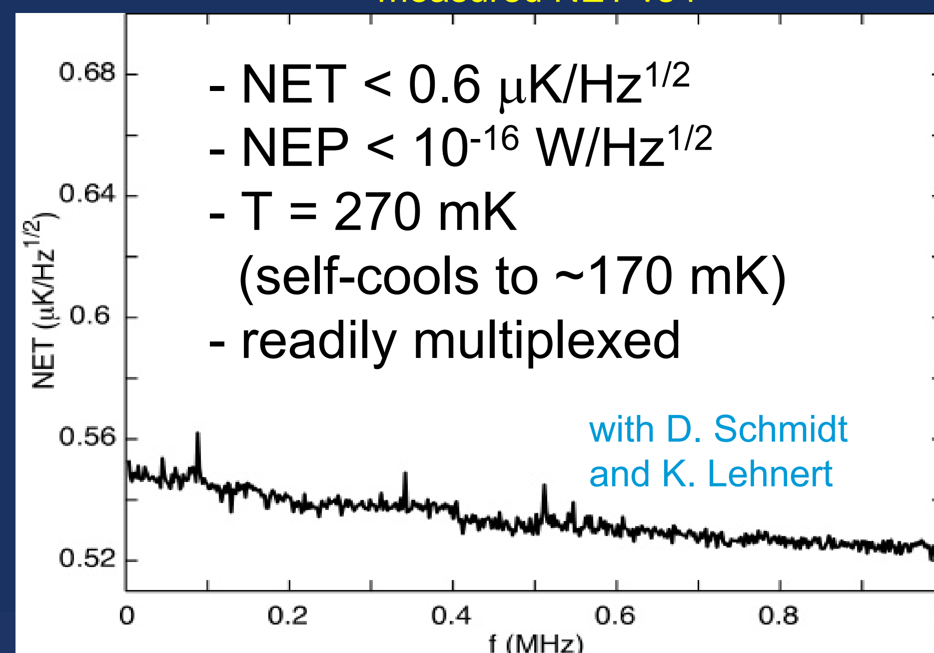
- Sensor = NIS junction operated as a detector.



device photo



measured NET vs f



Future prospects

- Detector array scale

  10,000 pixels are being fabricated for SCUBA-2. This is *far* from being a flight instrument.

  100-1000 kpixel cameras may be possible at shorter wavelengths with microwave readout techniques and new generations of room-temperature electronics, but ***significant*** development, $, and time is required.

  µWave SQUID MUX, µWave NIS, or KIDs (Zmuidzinas talk…)

- On-chip microrefrigeration

  Cooling 250 mK → 110 mK demonstrated, 80 mK is close

  Cooling 50 mK → < 10 mK is feasible, a path to ultra-low NEP detectors.

- All of these techniques are compatible with antenna-coupled, polarization-sensitive pixels.